Complete citation for malan's article

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38. The Uranium Mining Industry and Geology of the Monument Valley and White Canyon Districts, Arizona and Utah

ROGER C. MALAN*

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Illustrations

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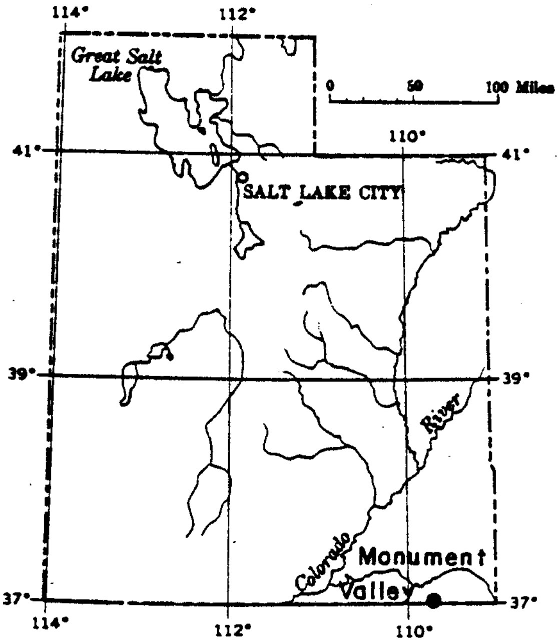
Tables



ABSTRACT

The Monument Valley and White Canyon districts are in northeastern Arizona and southeastern Utah. Exploration and mining for uranium has been conducted in these districts since the late 1940's. In July 1965, ore reserves plus ore production at 174 properties were approximately 3.3 million tons of ore containing about 19 million pounds U_3O_8, of which about 10 per cent remained in reserves. The two largest mines, Monument No. 2 and Happy Jack, together account for about 45 per cent of the sum of production and reserves. Approximately half the deposits in these districts contain less than 1000 tons of ore.

Nearly 5000 feet of Permian, Triassic, and Jurassic sedimentary rocks, mainly continental in origin, are exposed in these districts. All the important uranium deposits are in the Shinarump, the basal member of the Chinle Formation of Triassic age. The Shinarump lies on a widespread unconformity. It is composed of fluvial sediments, generally less than 100 feet thick, that were deposited by streams flowing from a source to the south.

Most of the deposits are in an arcuate belt, convex to the west. This belt, 3 to 12 miles wide, extends from Monument Valley northward nearly 130 miles. It is along the western flank of the ancient Monument Valley-Monticello upland, an area that was slightly uplifted at the beginning and again at the end of deposition of the Shinarump. Erosion and subsequent reworking of the Shinarump sediments in the vicinity of this upland are postulated to have made possible the transportation, in solution, of the uranium contained in these sediments. The soluble uranium probably was carried by migrating ground water into sites favorable for precipitation in Shinarump beds bordering the upland. Thus, the original very small amounts of dispersed uranium in the early Shinarump sediments were accreted in the favorable belt where the accumulations of carbonaceous plant remains and their decay products provided a persistent reducing environment.

INTRODUCTION

The Monument Valley and White Canyon districts cover about 3000 square miles in the central portion of the Colorado Plateau in northeastern Arizona and southeastern Utah (Figure 1). In these districts, deep canyons dissect a high tableland. Altitudes range from 4000 to 9000 feet. Most of the uranium deposits in these districts are in an arcuate belt which is 130 miles long and between 3 and 12 miles wide.

A study by the U.S. Atomic Energy Commission of the uranium resources in the Monument Valley and White Canyon districts was started in 1962 and completed in 1964; it is the basis of this paper. This project, originally assigned to R. G. Young and E. A. Noble, was completed by the present author. Many of the original stratigraphic interpretations, ideas on the origin of the uranium, and determination of environmental favorability, developed during the time when R. G. Young was in charge of the project, were later reported by Young (23). As a result of subsequent investigations, some of the earlier ideas have been modified by the writer in this report.

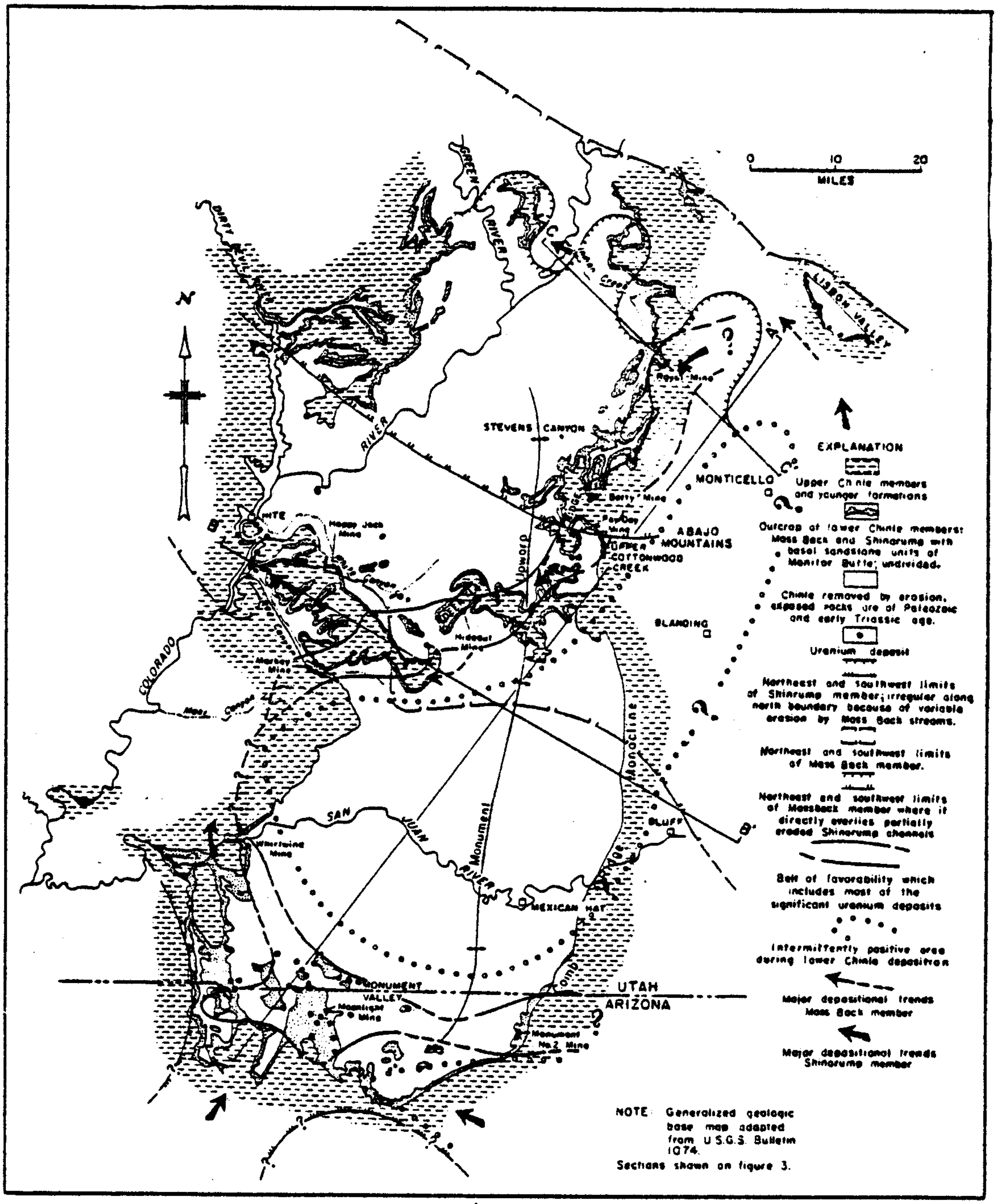


FIG. 1. *Generalized Geologic Map of the Monument Valley and White Canyon Districts, Arizona and Utah.*

About 174 properties with recorded production and/or reserves and about 100 additional occurrences without production or reserves were investigated. Stratigraphic sections of the lower Chinle Formation were measured at many localities and samples were collected for petrographic study. Fluvial channels at the base of the Chinle Formation of Triassic age, which are the sites for nearly all the uranium deposits, were mapped on aerial photographs.

The channel segments were correlated insofar as was possible, and, by projections, a complex paleodrainage system was reconstructed.

The helpful suggestions and the critical review of this paper by E. W. Grutt, Jr., U.S. Atomic Energy Commission, and R. P. Fischer, U.S. Geological Survey, are gratefully acknowledged. The author also wishes to express his appreciation for the helpful cooperation given him by mine operators and owners on numerous occasions.

URANIUM INDUSTRY

History

WHITE CANYON The copper, which is associated with many of the uranium deposits in the White Canyon district, was first discovered in the 1880's. B. S. Butler (1) of the U.S. Geological Survey identified uranium minerals in the White Canyon area in 1920 at what is now the Happy Jack mine. The first recorded uranium production in the area was from the Fry 4 claim in 1946. Uranium mining at the Happy Jack mine, which subsequently was developed into the largest mine in the district, began in 1949. During that year, Vanadium Corporation of America constructed a small uranium mill on the Colorado River near Hite and operated it until 1953. Prospecting was intense from 1948 to 1951 in the White Canyon, Red Canyon, and Deer Flat portions of the district, and as a result many claims were staked. Drilling programs by the U.S. Atomic Energy Commission and U.S. Geological Survey in the early 1950's stimulated a new wave of prospecting and discovery in 1953 and 1954, extending the area of known deposits northeastward into the Elk Ridge locality.

Although the number of producing mines increased from 6 in 1952 to 47 in 1956, only 13 mines were active in July 1965. A total of 113 mines have contributed to the total production. Production for a single year was greatest in 1958.

MONUMENT VALLEY The Monument No. 2 mine, discovered by a Navajo in 1942, was developed into the first producing uranium mine in Monument Valley in 1948.

In the late 1940's and early 1950's, many deposits, small to medium in size, were discovered in paleochannel exposures at rim outcrops. In 1955 and 1956, a cluster of important deposits including the Moonlight mine was discovered by Industrial Uranium Corporation in buried channels at moderate depths in the central portion of the Monument Valley district. Production in Monument Valley reached a peak in 1955, when 14 mines were operating.

Most of the ore that has been produced from the Monument No. 2 mine has been beneficiated in an upgrader located at the mine site. From 1948 to 1957, ore from other mines in Monument Valley was shipped to mills on the Colorado Plateau outside Monument Valley. A mill at Mexican Hat, Utah, constructed by Texas Zinc Minerals Corporation in 1957, was operated until March 1965. While it was operating, this mill processed most of the ore produced in Monument Valley except that from the Monument No. 2 mine. It also processed most of the ore produced in the White Canyon district. Since March 1965, most of the ores formerly treated by the Texas Zinc Minerals mill have been sent to the Atlas Minerals Corporation mill at Moab, Utah, for processing.

The Monument No. 2 mine has produced about 60 per cent of the ore mined in the district. Fifty-three properties in all have produced uranium, but only 4 mines were operating in July 1965.

Production and Reserves

There are 54 properties in Monument Valley and 120 in White Canyon with either available reserves or reserves and recorded production. As of July 1, 1965, the sum of the production and the remaining available reserves for the two districts combined was about 3,300,000 tons averaging 0.29 per cent U_3O_8 or about 19,000,000 pounds U_3O_8; 49 per cent of this total was credited to the Monument Valley district and 51 per cent to the White Canyon district. In July 1965, ore reserves in Monument Valley and in White Canyon were about 96,000 and 217,000 tons respectively.

Exploration

In Monument Valley, about 1.1 million feet of drilling, resulting in the discovery of about 1.448 million tons of ore, has been done for an estimated total cost of \$1.5 million. The estimated average drilling costs per ton of ore and per pound U_3O_8 have been \$1.04 and \$0.16 respectively. The tons of ore developed per foot of drilling has been about 1.3.

In the White Canyon district, about 1.2 million feet of drilling, resulting in the discovery of about 1.864 million tons of ore, has been done for an estimated total cost of about \$2.76 million. The estimated average costs per ton of ore and per pound U_3O_8 have been $1.48 and $0.28 respectively. The tons of ore developed per foot of drilling has been about 1.6. The drilling cost per ton of ore developed ranges from $0.25 to over $5.00.

In places where the depths to the base of the Shinarump do not exceed 300 feet, holes are drilled in an irregular pattern of fences, and holes are usually spaced 25 to 100 feet apart. Where hole depths are between 300 and 500 feet, the spacing of drill holes is usually between 100 and 500 feet. Nearly all drill holes are less than 500 feet in depth; however, 11 holes in the vicinity of the Happy Jack mine in White Canyon were drilled to an average depth of 1100 feet.

An estimated 95 per cent of all the drilling in the Monument Valley and White Canyon districts has been by rotary non-core methods. Current drilling cost is about $1.50 per foot of hole.

Mining

Nearly all mining in the two districts is underground. The only significant exception is at the Monument No. 2 mine in Monument Valley where open-pit mining is used. Underground mining methods vary from regularly spaced pillars at the Happy Jack mine in White Canyon to random rooms and pillars in medium size mines, to "drift mining" in the narrow, small deposits.

In about 90 per cent of the underground mines, adit or shallow incline access is possible from canyon rims. Shafts or steep inclines are used for access to deposits that are more remote from such rims.

GEOLOGY

Geologic History

About 5000 feet of Permian and Triassic sediments, mainly continental in origin with minor marine interruptions, were deposited in the area of study (Figure 2). The following simplified stratigraphic history of the Cutler and Chinle Formations is based on AEC observations and on the studies of McKee (16) and Stewart (17).

The Cutler Formation of Permian age was deposited by westward-flowing streams heading in the ancient Uncompahgre highland in southwest Colorado and emptying into a slowly subsiding basin. The facies grade from a conglomeratic arkose near the ancient highland to mainly red siltstone in the basin. During periods of isostatic adjustment in the basin, the eolian Cedar Mesa and De Chelly Sandstone Members of the Cutler Formation were deposited.

Following Cutler deposition, a shallow sea advanced from the northwest into the subsiding basin. During this time, red beds of the Moenkopi Formation of Triassic age were deposited in tidal flats in advance of the shallow sea. Streams continued to flow from the Uncompahgre highland westward into the basin.

Deposition of the Moenkopi stopped with regional uplift of the basin. This uplift started a period of erosion during which channels were cut into the Moenkopi sediments by streams flowing generally northward from a highland area in southern or central Arizona and southern New Mexico. This highland, where granitic and volcanic rocks were exposed, was the main source of the sediments that formed the Chinle Formation of Triassic age. The earliest Chinle sediments, those that formed the Shinarump Member, were carried by the northward-flowing streams and were deposited mainly in stream channels over a wide area in northern Arizona and southern Utah. In the area northeast of Monument Valley and southeast of White Canyon, however, these sediments were eroded shortly after deposition as a result of minor uplift in that area. Volcanic activity increased in the Arizona and New Mexico highlands during the time of deposition of the upper members of the Chinle Formation. These upper members are composed of as much as 900 feet of tuffaceous sediments.

Stratigraphy

All the important uranium deposits in the Monument Valley and White Canyon districts are in the rather thin Shinarump Member of the Chinle Formation. In a few cases, ore extends downward a few feet into the underlying Moenkopi Formation. The following stratigraphic descriptions are restricted to the lower members of the Chinle Formation.

The Chinle Formation unconformably overlies the Moenkopi and crops out throughout much of the area (Figure 1). The Chinle, which ranges in thickness from 500 to 1200 feet, has been subdivided by Stewart (17, p. 500) into seven members including, in ascending order, the Temple Mountain, Shinarump, Monitor Butte, Moss Back, Petrified Forest, Owl Rock, and Church Rock Members. The Temple Mountain Member, which may be a facies of the Shinarump, is a thin unit re-

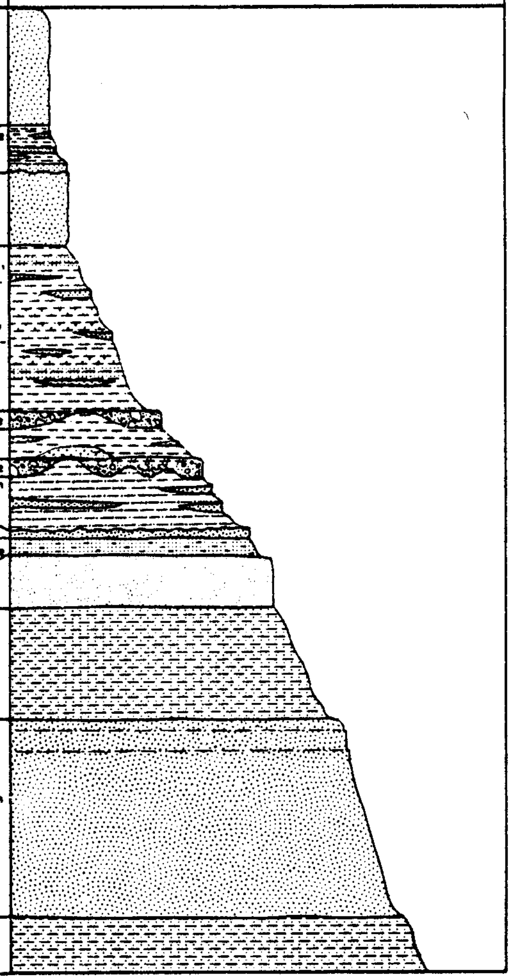
SYSTEM		STRATIGRAPHIC UNIT	THICKNESS	DESCRIPTION	COLUMN
JURASSIC	GLEN CANYON GROUP	NAVAJO SANDSTONE	300'- -665'	Gray to buff, massive, cross-bedded sandstone	
— ? —	GLEN CANYON GROUP	KAYENTA FORMATION	130'- -260'	Interbedded, red sandstone and reddish-brown siltstone and mudstone	
TRIASSIC	GLEN CANYON GROUP	WINGATE SANDSTONE	250'- -350'	Massive, orange to reddish-brown, fine-grained, eolian sandstone	
TRIASSIC	CHINLE FORMATION	UPPER MEMBERS	480'- -910'	Reddish-brown, thin-bedded, calcareous mudstones, siltstones and sandstones overlying gray to green, bentonitic clays and purple to chocolate brown mudstones with numerous sandstone lenses	
TRIASSIC	CHINLE FORMATION	MOSS BACK MEM.	0-150'	Gray, conglomeratic sandstone	
TRIASSIC	CHINLE FORMATION	MONITOR BUTTE MEMBER	0-250'	Variegated, bentonitic mudstone with sandstone lenses	
TRIASSIC	CHINLE FORMATION	SHINARUMP MEM.	0-250'	Congl. sandstone & carb. shale	
TRIASSIC		MOENKOPI FORMATION	0-450'	Interbedded chocolate brown siltstone and light brown fine-grained sandstone	
PERMIAN	CUTLER FORMATION	WHITE RIM MEMB.	0 — 50	Massive, white sandstone	
PERMIAN	CUTLER FORMATION	HOSKINNINI TONGUE	10'—150'	Reddish-brown silty sandstone	
PERMIAN	CUTLER FORMATION	DE CHELLY SANDSTONE MEMBER	0—450'	Massive, tan, fine-grained eolian sandstone	
PERMIAN	CUTLER FORMATION	ORGAN ROCK TONGUE	170'- -750'	Reddish-brown siltstone and fine-grained sandstone	
PERMIAN	CUTLER FORMATION	CEDAR MESA SANDSTONE MEMBER	450'— -1200'	Massive, buff-white, eolian sandstone with thin red siltstone partings near top	
PERMIAN	CUTLER FORMATION	HALGAITO TONGUE	0-465'	Reddish-brown siltstone and fine-grained sandstone	

FIG. 2. *Generalized Stratigraphic Column of the Monument Valley and White Canyon Districts, Arizona and Utah.*

stricted to the San Rafael Swell northwest of the White Canyon district.

The Shinarump, the lowermost member of the Chinle, consists of fluvial sediments which were deposited in stream channels and flood plains. These fluvial sediments are composed of lenticular beds of sandstone, conglomerate, siltstone, and mudstone; they contain abundant fragments of carbonized wood and minor amounts of silicified wood. The carbonaceous debris is partially replaced by ore minerals in the uranium deposits. Individual beds range from a few inches to 40 feet in thickness. The sandstone is commonly light buff and medium- to coarse-grained and is usually conglomeratic at the base. The pebbles are predominately quartzite, quartz, and chert with some limestone, sandstone, siltstone, and mudstone. Calcite is the most common cementing material in the sandstone and conglomerate. Depositional features include longitudinal bars, which fill scours, and torrential cross-bedding. The thickness of the Shinarump ranges from about 10 feet to nearly 250 feet. Preceeding the deposition of the overlying Monitor Butte Member, Shinarump flood plain and channel sediments, in areas peripheral to uplands, were thinned by erosion; channel sediments in the uplands were either truncated or completely removed.

The Monitor Butte Member of the Chinle Formation, which unconformably overlies the Shinarump Member (23), is composed of a thin, discontinuous basal sandstone unit overlain by a thick mudstone unit. This sandstone unit has been included in the Shinarump by other investigators (20). The areal distribution of the basal sandstone unit of the Monitor Butte and the distribution of the Shinarump are similar. This basal sandstone unit is a buff to cream, conglomeratic, variably carbonaceous, quartzose sandstone cemented with calcite or clay. Pebbles in the conglomerate are gray and pink quartzite and quartz and are as large as 4 inches in diameter. The basal sandstone unit changes from a nearly continuous blanket of sandstone in Monument Valley to less continuous lenticular beds of sandstone which interfinger with beds of mudstone in White Canyon. In the White Canyon area, the zone of transition from the basal sandstone unit to the overlying mudstone unit of the Monitor Butte is characterized by a gradual decrease in the number of sandstone lenses. The mudstone unit is composed of grayish-green, micaceous mudstone and claystone beds and a few thin conglomeratic sandstone beds.

The Monitor Butte thins from about 250 feet in Monument Valley to a featheredge northward along the north part of Elk Ridge (Figures 1, 3). North of Elk Ridge, the Moss Back Member of the Chinle rests unconformably either on erosional remnants of the Shinarump or on the Moenkopi. The northward thinning of the Monitor Butte is believed to be a result of truncation during the period of erosion which preceded deposition of the Moss Back Member.

The Moss Back Member of the Chinle Formation, which is the host rock for the large uranium deposits in the Lisbon Valley area, is comprised of buff to gray sandstone and conglomeratic sandstone with some conglomerate, siltstone and mudstone. Quartzite and chert pebbles are abundant in the conglomerates. In places, limestone pebbles predominate. The Moss Back is present only in the northern portion of the area (Figure 1). It extends from near White Canyon on the southwest to somewhat beyond the Lisbon Valley area on the northeast. From the northeast to the southwest, the Moss Back overlaps a succession of truncated sediments including the Cutler Formation, Moenkopi Formation, and the Shinarump and Monitor Butte Members of the Chinle Formation (Figure 3). The predominant regional trend of streams that deposited the Moss Back was northwesterly; however, local southwesterly trends are present in the upper Indian Creek area and along Elk Ridge (Figure 1). The Moss Back ranges in thickness from a featheredge to 150 feet. It interfingers with mudstone of the overlying Petrified Forest Member of the Chinle.

The upper members of the Chinle including the Petrified Forest, Owl Rock, and Church Rock are comprised of 500 to 1000 feet of varicolored mudstone and siltstone with minor sandstone, conglomerate, and limestone. They contain no known uranium deposits in the Monument Valley and White Canyon districts.

Shinarump Channel Systems

The recognition of Shinarump channels and channel patterns (Figure 4) is important, because all of the significant uranium deposits in the Monument Valley and White Canyon districts are in these channels. In the 1950's, several investigators including Reinhardt (3), Grundy and Oertell (9), Larsen and Schoen (11), Evensen and Gray (7), Johnson and Thordarson (14), Lewis and Trimble (15), Thaden, *et al.* (21), Lewis and Campbell (24), and Witkind and Thaden (20), studied channels and mapped channel segments on the basis of outcrops and available data from drill holes. Their work provided a background of information useful in this study.

As used in this report, Shinarump channels are the courses of paleostreams which were incised into the Moenkopi and which were filled with fluvial sediments. Scours are the discontinuous, stream-incised, cut-and-fill components within the channels. These scours developed at stages during the lateral shifting of the main stream channel. Sediments in scours in the lower portions of channels are the hosts for the uranium deposits. Channels in Monument Valley are U-shaped in cross section, contain mainly sandstone and conglomerate, are quite narrow, and commonly contain only one ore-bearing scour. Channels in White Canyon are broader; carbonaceous mudstone and siltstone are more abundant, and some channels contain as many as three separate subparallel ore-bearing scours.

In unexplored ground, channels can be projected with reasonable accuracy up to distances of about one mile between exposures on opposite sides of a mesa. Lithologic similarities, the common trends of longitudinal bars, and the common attitude of cross-laminations aid in correlating between two exposures. Over distances greater than a mile, projections for some channels can be made on the basis of geologic features in the Monitor Butte and Moss Back Members. Slumping in the Monitor Butte often occurred above the courses of

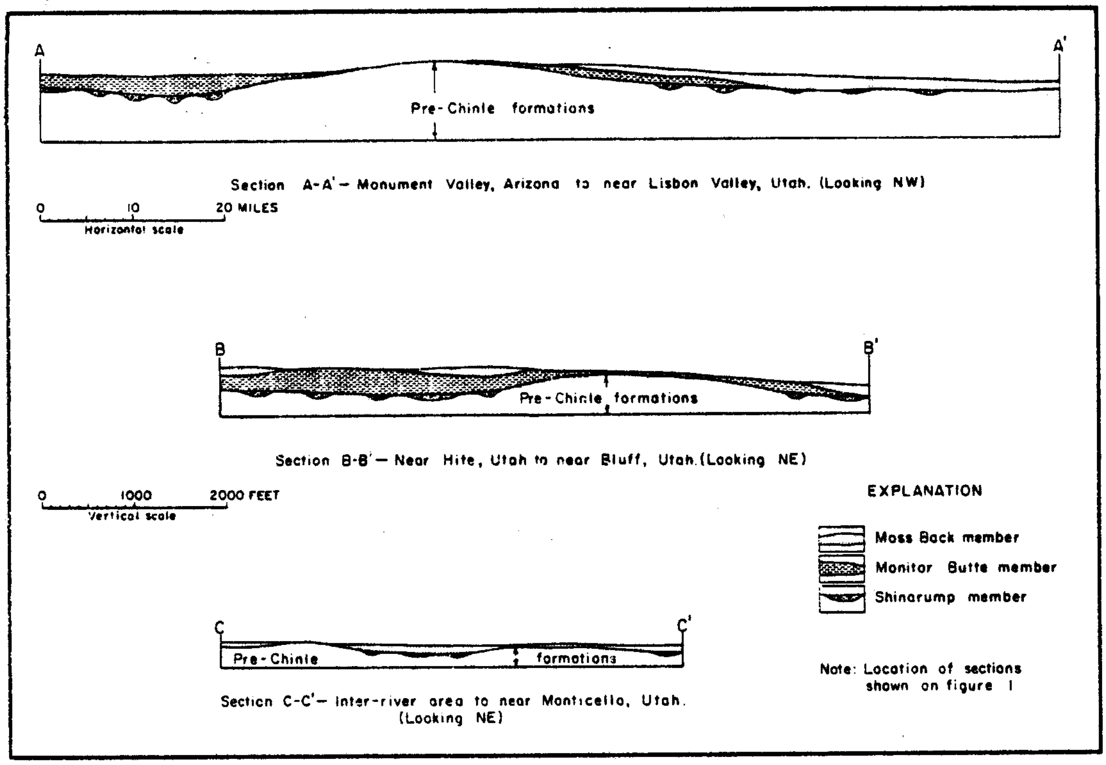


FIG. 3. *Generalized Geologic Sections of the Lower Part of the Chinle Formation at the Close of Deposition of the Moss Back Member.*

those Shinarump channels that are filled with mudstone, and, at these places, the Moss Back is also locally thicker.

Where the Moss Back and Monitor Butte are removed by erosion, Shinarump channels commonly yield a characteristic topographic expression. Channels filled with carbonaceous mudstone commonly form low ridges, for the Shinarump mudstone is generally more resistant to erosion than is the Moenkopi Formation. Shinarump sandstone in sandstone-filled channels, on the other hand, is commonly highly jointed, and hence these channels are more easily eroded than the Moenkopi; many present day stream courses and valleys follow these sandstone-filled channels.

Sandstone and conglomerate were deposited in places where the channels were narrow and had quite high gradients, whereas, carbonaceous mudstone was deposited in places where the channels were broad and meandering and had low gradients. The type of sediments deposited in the channels was determined by the position of the channels relative to an upland that was elevated at the beginning of deposition of the Shinarump. This upland, named the Monument Valley-Monticello upland in this report, most probably extended from Monument Valley to the vicinity of Monticello, Utah (Figure 1). In the White Canyon district, the facies of the Shinarump changes from dominant sandstone along the western flanks of the Monument Valley-Monticello upland to dominant mudstone in an adjacent lowland to the west. The favorable belt in which nearly all of the important uranium deposits in White Canyon are located is this zone of transition between sandstone on the flanks of the upland and mudstone in the adjacent lowland.

Variations in gravel size, orientation of dips in cross-strata, and diagnostic fossils in gravel indicate that the Shinarump was deposited by streams flowing northward from a source area in southern New Mexico and southern or central Arizona (16, p. 24; 17, p. 506, 523). The positions of the eastern and northern margins of the ancient upland (Figure 1), which extended from Monument Valley to Monticello, are inferred from subsurface data from a few widely-spaced oil tests. Fluvial sandstones of the basal Chinle, which were penetrated by these holes drilled east of the ancient upland, may be either the Shinarump or the

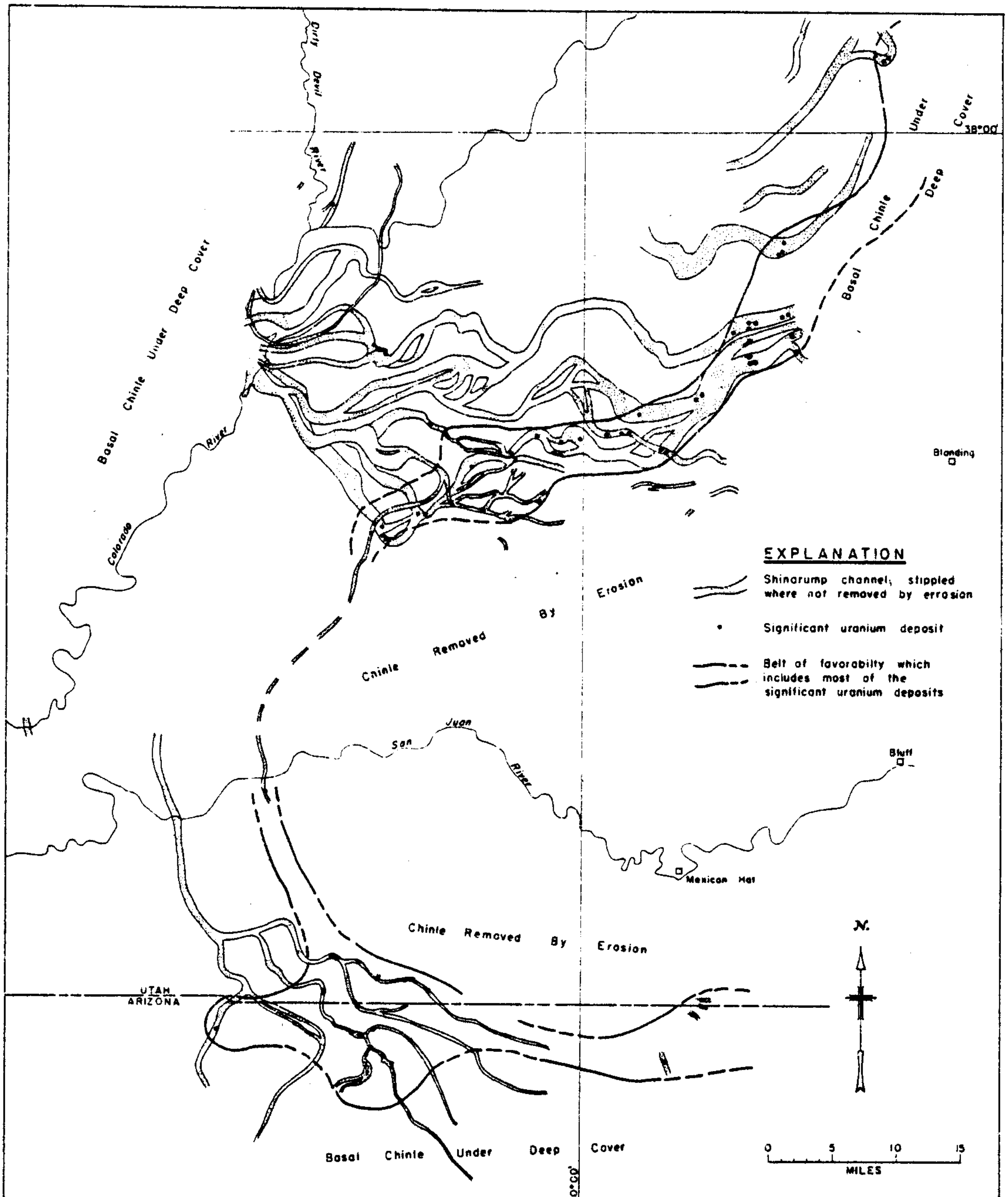


FIG. 4. *Shinarump Channel Systems in the Monument Valley and White Canyon Districts, Arizona and Utah.*

Moss Back, or perhaps both of these members. These fluvial sandstones east of the ancient upland may have been deposited by streams flowing northerly or northwesterly from the highland in southern or central Arizona and southern New Mexico. Streams flowing to the northwest may have been diverted to the northeast along the east margin of the barrier formed by the Monument Valley-Monticello upland. Johnson and Thordarson (14) suggest that streams depositing the Shinarump sediments in the White Canyon and Elk Ridge localities may have originated in the ancestral Uncompahgre highland to the northeast. However, the development of such drainage patterns between the ancient Uncompahgre highland and the White Canyon district might have been poor because of the barriers formed by the northwest-trending salt anticlines in the Paradox Basin. The Chinle internally thins and nearly pinches out over the core of the Paradox Valley anticline (12, p. 50). The author favors a source to the south or southeast for the Shinarump in the Monument Valley and White Canyon districts and for the Shinarump (?) east of the ancient upland extending from Monument Valley to Monticello.

The Monument Valley-Monticello upland was elevated in the early stages of development of the Shinarump drainage system. Evidence for the existence of the upland during the development of the Shinarump drainage system is the parallelism of the courses of many larger channels to the western margin of the upland in the northern portion of the White Canyon district (Figures 1 and 4). Farther south, the streams flowed westerly away from the upland in response to the regional gradient. The sediments deposited by smaller tributary streams draining this earlier upland and part of the sediments deposited in the large channels in the adjacent lowland were later eroded during a period of renewed uplift of the Monument Valley-Monticello upland. This uplift probably did not exceed 500 feet (Figure 3). The basal sandstone unit of the Monitor Butte Member consists partly of Shinarump sediments that were reworked during this period.

Evidence of meander cutoffs, shifting of channels, and anastomosing streams are present in the Shinarump drainage system (Figure 4). In parts of the White Canyon area, there are two rather distinct generations of channels in the Shinarump. The younger channels commonly cut through the older channels and locally form quite different directional patterns. Where these two systems can be distinguished, the more important uranium deposits are always in the younger system.

Structural Geology

The Monument Valley and White Canyon districts are located in the southern portion of the Monument Upwarp, a large asymmetric, north-trending anticline of probable Laramide age (Figure 1). The western flank of the upwarp dips 2° to 4° west into the Kaiparowits and Henry Mountains Basins in central Utah; the upwarp is bounded on the east and southeast by the Comb Monocline which dips steeply to the east. Several north- and northeast-trending asymmetric anticlines and associated synclines are superimposed on the upwarp. Small, high-angle, normal faults are present throughout the region, but they are most common in the northern portion. West- to southwest-trending faults bound well-defined grabens in the area west of the Abajo Mountains.

URANIUM DEPOSITS

Distribution and Habit

With the exception of the Happy Jack mine and its satellite deposits, all important deposits in the Monument Valley and White Canyon districts are restricted to an arcuate belt of favorable sandstone 3 to 12 miles wide and about 130 miles long. This favorable belt extends from Monument Valley on the south, through White Canyon and Elk Ridge, to Indian Creek on the north (Figure 1). The only place where its continuity has not, as yet, been established is the unexplored, deeply buried segment of Chinle sedimentary rocks 15 miles long between the San Juan River and Red Canyon. Finch (13) named the area southeast of this buried segment the Monument Valley Belt and the area to the northeast the East White Canyon Belt. Young (23) has proposed the name Monument Mineral Belt to include the entire belt. The belt is postulated to coincide with the distribution of favorable sandstones of the Shinarump along the west margin of the Monument Valley-Monticello upland.

Uranium deposits are primarily restricted to favorable carbonaceous sandstone and conglomerate beds in the lower part of the Shinarump Member of the Chinle Formation; however, in a few mines such as the Moonlight and Happy Jack, ore extends downward as much as 15 feet into the siltstone of the underlying Moenkopi. The channel at the Monument No. 2 mine locally scoured through the underlying Moenkopi Formation and the Hoskinnini Tongue of the Cutler Formation into the De Chelly Sandstone Member of the Cutler Formation. At that mine, vanadium ore extends downward into the De Chelly for 10 to 20 feet.

As viewed in plan, ore deposits are linear, non-linear, and curvilinear in outline. In the linear deposits, the ratio of length to width is commonly at least 5 to 1 and may reach 50 to 1. Most of the deposits in the Monument Valley and White Canyon districts are linear.

Typical examples are the Monument No. 2 and Markey mines. Non-linear deposits are irregular amoeba-shaped or somewhat eliptical in outline. Length to width ratios range from 1 to 1 to 5 to 1. There are only a few non-linear deposits; the Happy Jack and Betty mines are of this type. Curvilinear deposits are strongly elongated and broadly curving with parallel to subparallel scours controlling the local ore trends. The ratio of length to width is about the same as in linear deposits. Meander loops in Shinarump channels were favorable sites for ore deposition. An example is the Hideout mine where several separate, subparallel, curving ore trends occupy scours formed at different stages in the development of a major meander.

Ore bodies consist of closely-spaced, lenticular ore pods which are generally concordant with bedding. Single ore pods range from a few feet to a few hundred feet in length and from less than one foot to 12 feet in thickness. The average length ranges from about five to ten times the average width. Mineable ore is continuous in one mine for 7000 feet. Deposits range in size from a few tons to more than 800,000 tons. About half of the 174 deposits are smaller than 1000 tons in size and 96 per cent are smaller than 50,000 tons (Table I); only six deposits contain more than 50,000 tons each. The largest deposit contains nearly one-third of the sum of total production and remaining available reserves in the Monument Valley and White Canyon districts. The ten largest deposits contain about 70 per cent of the combined total production and reserves.

Most of the ore now being mined is unoxidized. Except for the large Monument No. 2 deposit, nearly all the surficial oxidized deposits have been mined.

Copper and Vanadium

The uranium deposits contain variable amounts of copper and vanadium. Ores from the Monument No. 2 mine in the eastern part of the Monument Valley district contain average amounts of 1.40 per cent V_2O_5 and nil copper. In the other Monument Valley deposits for which some data are available, vanadium ranges from 0.22 per cent to 0.81 per cent and copper ranges from 0.29 per cent to 2.50 per cent; weighted averages are 0.60 per cent V_2O_5 and 0.71 per cent copper. In White Conyon, the vanadium content of those deposits for which some data are available ranges from 0.02 per cent to 1.20 per cent V_2O_5; the weighted average is 0.23 per cent V_2O_5. In the White Canyon deposits, copper ranges from 0.12 per cent to 1.30 per cent and averages 0.69 per cent. These averages for each district are not representative, because they are based solely on production from mines for which the vanadium and copper content was recorded. Although incomplete, the above data are indicative of variations and relative orders of magnitude.

In general, the vanadium content of ores in Monument Valley decreases from east to west, but copper increases from east to west. The copper content in the White Canyon dis-

TABLE I. Distribution of Deposits by Locality and Size, Monument Valley and White Canyon Districts

Locality	Number of Deposits [1]	Tons [2]	Distribution of Deposits by Size					
			Less than 1,000 T.	1,000 to 10,000 T.	10,000 to 50,000 T.	50,000 to 100,000 T.	100,000 to 500,000 T.	Greater than 500,000 T.
Monument Valley	54	1,448,000	29	11	12	0	1	1
White Canyon	46	713,000	28	13	4	0	0	1
Red Canyon	29	492,000	13	8	6	1	1	0
Deer Flat	11	279,000	2	6	2	0	1	0
Elk Ridge—upper Cottonwood	25	233,000	8	8	9	0	0	0
Stevens Canyon—upper Indian Creek	9	146,000	4	0	5	0	0	0
Total	174	3,311,000	84	46	38	1	3	2
Per cent of total			48%	26%	22%	.6%	2%	1%

[1] Includes deposits with production and/or available reserves as of 7/1/65.
[2] 7/1/65 available reserves plus production.

trict increases from east to west, but no pattern of distribution is evident for vanadium.

Mineralogy

In the unoxidized parts of the Monument No. 2 mine, uraninite and coffinite are associated with vanadium minerals such as montroseite, corvusite, doloresite, and vanadium hydromica. Sulfides of iron, copper, and lead are also present. Oxidized ore minerals from this mine are tyuyamunite, carnotite, hewettite, and navajoite. All these minerals are associated with oxides of iron.

In other mines in Monument Valley and White Canyon, the suite of unoxidized minerals is the same as that at the Monument No. 2 mine, but copper sulfide minerals are more abundant, and montroseite is less abundant.

The uranium minerals, torbernite, uranophane, uranopilite, betazippeite, and johannite have been identified in samples from oxidized deposits. Malachite, azurite, and hydrous copper and iron sulfates are common accessory minerals.

Calcium carbonate is present in ore mostly as cementing material in the sandstone host rock. In Monument Valley mines, calcium carbonate ranges from 1.4 per cent to 10.3 per cent and averages 4.6 per cent. Calcium carbonate content generally seems to be inversely proportional to vanadium content in Monument Valley deposits. Analyses for calcium carbonate in White Canyon mines range from 1.3 per cent to 8.0 per cent and average 2.4 per cent; this is about half the average in Monument Valley mines. No relationship between calcium carbonate and vanadium content is evident in White Canyon mines. Calcium carbonate cannot be correlated with copper in either district. There is a quite high calcium carbonate content in the Royal mine near Indian Creek at the extreme northeastern end of the White Canyon district. Abundant calcium carbonate is present in lime-pebble conglomerate and calcareous sandstone in the Moss Back Member which overlies the Shinarump host rocks in this locality.

Ore Controls

The uranium deposits are most commonly localized in the more deeply scoured portions of Shinarump channels. These deeper scours occur on the outside of bends and in relatively straight portions of channels in those places where the less resistant beds of the Moenkopi were present. The deep scours were subsequently filled with longitudinal sand and gravel bars and carbonaceous debris. When the scours were filled and lower stream gradients were attained, the sandstone and conglomerate beds were covered by layers of silt and carbonaceous mudstones. In all probability, the transmissive coarse sediments provided the main pathways for uranium-bearing ground waters, and the carbonaceous debris in the sandstone, conglomerate, and overlying mudstone created the reducing environment necessary for precipitation of the uranium.

The Happy Jack deposit in White Canyon is outside the favorable belt within which nearly all the other significant deposits occur (Figure 1). The main Happy Jack deposit and its associated cluster of smaller deposits are nonlinear types. These deposits are confined to an area in which a sharp meander of a younger Shinarump channel crosses and scours into a broad bend in an underlying Shinarump channel which is filled with carbonaceous mudstone. These geologic conditions permitted large quantities of uraniferous ground water from the two channels to enter a single favorable environment. As evidenced by the large size of the Happy Jack deposit, the ore forming process must have been very efficient.

The Monument No. 2 mine, in eastern Monument Valley is a strongly elongated, northwest-trending, linear deposit in a channel situated along the northern flank of an upland which was uplifted at the close of deposition of the Shinarump (Figure 1). The southeastward segment of the channel, where it crosses the upland, was removed by erosion following the uplift. The original northwest inclination of the northwest segment of the channel was reversed to the southeast by uplift during Laramide time of the Gypsum Creek Dome which is an element of the larger Monument Upwarp. Most of this northwest segment was subsequently removed by erosion.

Genesis

The uranium in the deposits may have been derived from: (1) erosion and leaching of large masses of granitic rocks, arkose, and tuffaceous sediments or (2) from hypogene fluids generated by magmatic activity. The author favors the first theory.

Leaching of Granitic, Arkosic, and Tuffaceous Rocks The uranium deposits of the Monument Valley and White Canyon districts may have been formed through multiple migration-accretion (5). Small amounts of uranium, vanadium, and copper which were leached from rocks actively undergoing erosion were introduced into the Shinarump channel systems by surface and ground waters during or soon after deposition of the channel sands. Although no definitive evidence is on hand, the uranium may have been obtained from the weathering and leaching of granitic igneous rocks, arkosic sandstones, and tuff beds containing trace amounts of uranium in the source areas of the sediments. It is postulated that uranium, as the uranyl ion, moved northward in ground water through the permeable channel sediments until it was fixed by reduction in the vicinity of accumulations of organic debris. This organic material could have been the reducing agent, or it could have supplied the energy source for anaerobic bacteria which generate hydrogen sulfide, a powerful reducing agent capable of reducing the water-soluble uranyl ion to the insoluble uranous state (10). Minor and dispersed concentrations of uranium, vanadium, and copper, few of which may have been large or rich enough to mine, thus were formed soon after sediments accumulated in the Shinarump channel systems.

Following deposition of the Shinarump, renewed upwarp of large areas that coincided in part with the already existing uplands took place north and southeast of Monument Valley and east of the White Canyon district (Figure 1). The minor and dispersed occurrences of uranium deposited initially in Shinarump sediments were solubilized by oxidation during the erosion of channels from higher parts of the newly uplifted areas and the partial erosion of numerous large channels in the adjacent prevailing lowland. This remobilized uranium was transported by ground waters into reducing environments in the channels that remained along the lower flanks of the rejuvenated uplifts. In the White Canyon district, the transition zone between the upland and lowland is characterized by a gradual change from permeable sands in channels on the flanks of the uplifts to impervious carbonaceous mudstone in these same channels in the lowlands. In Monument Valley, the most favorable places for uranium deposition were the heterogeneous channel sandstones that were deposited where anastomosing streams converged (Figure 4).

HYPOGENE FLUIDS GENERATED BY MAGMATIC PROCESSES The presence of a few conspicuous Tertiary plugs and many small dikes of lamprophyric rock (20, p. 51) in Monument Valley and laccolithic intrusives of hornblende andesite porphyry (8, p. 144) in the Abajo Mountains, a few miles east of the northern portion of the favorable belt has suggested to some workers a possible magmatic origin during Tertiary time for uranium in the Monument Valley and White Canyon districts. Williams (2, p. 148) believes the Monument Valley intrusives to be of middle to late Pliocene age. Hunt (6, p. 82) suggests that the Abajo intrusives are of middle Miocene age, and Witkind (22, p. 104) provisionally proposes a Miocene or Pliocene age. Finnel (18, p. 52) suggests that the ore solutions moved upward along buried faults from a deep source during the Laramide orogeny. All these ages are much younger than the age of 180 m.y. for the uranium as proposed by Young (23) and favored by the author.

A number of isotopic age determinations on samples from Monument Valley and White Canyon have been made. Pb^{206}/U^{238} age determinations of only slightly altered uraninite samples from the Monument No. 2 mine range from 60 to 100 m.y. and average 78 m.y. (20, p. 96). The ages of samples from the Happy Jack mine are within this same range (4, p. 15). Ages of samples from basal Chinle deposits in other areas are much older. Age determinations on samples from Lisbon Valley, Utah, and Cameron, Arizona, average 150 m.y. and 175 m.y. respectively (19). As commented upon by Young (23, p. 872), the isotopic ratios that result in wide differences in age may reflect the complicated redistribution of uranium during the deposition of the lower Chinle and perhaps during the Laramide orogeny.

To the author, the most compelling evidence against a magmatic hydrothermal origin of the uranium deposits is that the favorable belt is transverse to the Monument Upwarp of Laramide age and the distribution of deposits is not spatially related to intrusives or to patterns of faults, fractures, and folds within the upwarp. If the deposits were Tertiary in age, some better correlation with these structures would be expected.

GUIDES TO PROSPECTING

Certain geologic factors seem to have influenced the localization of uranium deposits in the Monument Valley and White Canyon districts. An understanding of the geologic events is helpful in prospecting for new deposits in these districts. Some important considerations are:

1. The belt of important deposits in the

White Canyon district is marginal to the ancient Monument Valley-Monticello upland. The possible genetic relationship between deposits in the White Canyon district and the large deposits in the Lisbon Valley area, 20 miles northeast of the Royal mine near Indian Creek, warrants consideration. The Lisbon Valley area is also situated on the flank of an ancient upland, the ancestral Lisbon Valley anticline. The host rock is the Moss Back Member of the Chinle which overlies the widespread unconformity at the base of the Chinle in that area.

2. In the White Canyon district, nearly all the important deposits are situated within a belt that coincides with the facies change in the Shinarump from predominately sandstone to predominately carbonaceous mudstone.

3. Uranium deposits occur only in the lower portions of Shinarump channels which are trough-shaped depressions filled with sandstone, conglomerate and variable amounts of carbonaceous mudstone.

4. Uranium deposits may exist in channels which are obscured by overburden at the rims of mesas within the belt of favorability. In localities such as Elk Ridge, where overburden is extensive, more exploratory rim stripping may be warranted.

5. Undiscovered uranium deposits may exist in Shinarump channels in portions of the belt in which the Shinarump is deeply buried by younger members of the Chinle.

6. The probable courses of buried Shinarump channels can often be inferred by correlating the channel segments which have been established through exploration and reconstructing the channel patterns.

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